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# **Hysteresis Loss Analysis of Soft Magnetic Materials Under Direct Current Bias Conditions (Preprint)**

**Zafer Turgut, Hiroyuki Kosai, Tyler Bixel, James Scofield, S. Lee Semiatin, and John Horwath**

**Electrical Systems Branch  
Power and Control Division**

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<b>14. ABSTRACT</b> Direct current bias related hysteresis loss characteristics of three commercially available magnetic materials: (1) an iron based Metglas tape core, (2) a Sendust powder core, and (3) a Mn-Zn based ferrite in both un-gapped and gapped configurations were studied. The measurements are conducted for a fixed external field Hext, a fixed flux swing (DB), and a fixed maximum forward magnetization (Bmax) as a function of the external bias field. In all the measurements, a direct correlation is found between permeability and measured loss values as a function of dc bias field. Increased hysteresis losses are measured in the magnetization rotation region in which classical domain theory predicts minimal losses. The observed trends are discussed within the frame work of classical domain theory.					
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# Hysteresis Loss Analysis Of Soft Magnetic Materials Under Direct Current Bias Conditions

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## Abstract

Direct current bias related hysteresis loss characteristics of three commercially available magnetic materials: (1) an iron based Metglas tape core, (2) a Sendust powder core and (3) a Mn-Zn based ferrite in both un-gapped and gapped configurations were studied. The measurements are conducted for a fixed external field  $H_{ext}$ , a fixed flux swing ( $\Delta B$ ) and a fixed maximum forward magnetization ( $B_{max}$ ) as a function of the external bias field. In all the measurements, a direct correlation is found between permeability and measured loss values as a function of dc bias field. Increased hysteresis losses are measured in the magnetization rotation region in which classical domain theory predicts minimal losses. The observed trends are discussed within the frame work of classical domain theory.

## I. INTRODUCTION

In classical domain theory of ferromagnetic materials<sup>1</sup>, a bulk ferromagnet experiences three distinct magnetization processes when magnetized from its virgin state: (1) a reversible displacement of domain walls at infinitesimal external fields, (2) an irreversible displacement of domain walls at intermediate external fields and (3) reversible magnetization rotation that occurs at high external fields and leads to saturation. A superimposed dc bias field introduces a predetermined domain configuration by magnetizing a ferrimagnetic or ferromagnetic material along its virgin magnetization curve and determines the permeability window in which the material operates. Depending on the magnitude of the dc bias and external fields, domain walls with lower activation energies may not contribute to the magnetization process and higher energy walls may be mobilized, which would not be activated otherwise. All these variations with an external bias field often result in distorted hysteresis loops and varying loss values.

Studying hysteresis losses under a dc bias field gives a unique opportunity of limiting the loss measurements to a specific area of interest i.e. irreversible displacement region, rotational region or a combination of them. Performing such loss studies in toroid or ring shaped specimens that are free from any demagnetizing fields and focusing only on quasi-static hysteresis losses that does not include any contributions from eddy currents represents the simplest picture possible to study. Properly annealed amorphous cores free from demagnetizing fields display domain widths as large as 4 mm in the form of slabs running parallel to the core's circumference<sup>2</sup>. These cores exhibit no maze or closure domains.

By definition, there should be little or no hysteresis loss associated with the rotational process. There is no irreversible wall motion and the only factor that contributes to coercivity is that the magnetization vector has to overcome the local magnetocrystalline anisotropy assuming that other anisotropies are absent. Therefore, amorphous materials, that lack crystalline periodicity, should exhibit no loss associated with rotational process. However, our measurements indicate that hysteresis losses increase in the rotational region.

## II. EXPERIMENTAL

A pair of commercially available Metglas<sup>®</sup> 2605SA1 type amorphous “U” shaped cores was formed into a rectangular core. The core dimensions were 30 mm high and 10 mm thick with inside window dimensions of 13 by 50 mm. The powder and ferrite cores were also off the shelf materials; the Sendust core dimensions were 33.4 mm outer diameter (OD), 19.9 mm inner diameter (ID), 9.3 mm thick and the Mn-Zn ferrite core dimensions were 31.0 mm OD, 18.9 mm ID, 16.1 mm thick. A 0.3 mm gap was introduced to the same ferrite core for repeated measurements. A set of primary and secondary windings, and a third winding that was used to introduce a bias field, were put on the core away from the joining surfaces. A hysteresisgraph was used for magnetic measurements and an external DC power supply was used to generate the bias field on the third winding. A series of quasi-static (dc) minor loops were taken at different maximum inductions,  $B_{\max}$  values ranging from 0.03 to 0.1 T and bias fields of 0 to 2060 A/m. The core was first demagnetized at a frequency of 100 Hz and a step size of 10 mT and then a predetermined bias field was introduced prior to each measurement. The hysteresis losses were calculated by integrating the measured minor loops. In all the measurements, the bias field was kept large enough to drive the cores to the knee and beyond in their respective magnetization curves except for the Sendust core which required external fields larger than the capability of the measurement setup employed in this study.

## III. RESULTS AND DISCUSSIONS

Figure 1.a shows whole dc loops and related permeability values (Fig. 1.b) of the studied cores. There are three ways of measuring hysteresis losses under a bias field; (1) using a predetermined external field  $H_{\text{ext}}$ , (2) driving the magnetic core to a fixed maximum forward magnetization ( $B_{\max}$ ) value, and (3) varying the external field in order to drive the core to a fixed flux swing ( $\Delta B$ ). The first two methods lead to contradicting conclusions. When the external field is kept constant, after the maximum permeability is reached, increasing bias field moves the material to a lower effective permeability value. As the effective permeability is reduced with increasing bias, the magnitude of flux swing gets smaller and smaller giving the false conclusion of decreasing hysteresis losses with increasing bias field. Results of such loss measurement are given in Figure 2 for a Metglas core as a function of dc bias at a fixed external field of 40 A/m. Due to the high asymmetry of the minor loops under dc bias and with the asymmetry strongly correlated to the permeability window operated, fixed  $B_{\max}$  measurements also give the false impression of increased losses with increasing bias in the vicinity of maximum permeability and decreasing losses at higher dc bias fields. Figure 3 shows measured hysteresis losses for the same Metglas core at a fixed  $B_{\max}$  of 0.1 Tesla. The origin of the observed behavior is easily understood by comparing the measured minor loops. Figure 4a depicts measured minor hysteresis loops of the Metglas core. With the application of external bias, hysteresis loops begin to become asymmetric and the degree of asymmetry increases in the vicinity of maximum permeability. As the bias field is increased to higher levels, asymmetry becomes less significant especially when the  $H_{\text{bias}} \pm H_{\text{app}}$  interval does not coincide with the field level where the maximum in permeability occurs. Similar loops are given in figure 4b for the un-gapped ferrite core on a finer scale in which the highest bias field corresponds to the field that maximum permeability is measured. Metglas and ferrite cores have comparable permeability curves (Fig. 1b) having the maximum permeability values of 4000 and 3700 respectively. Applied field values where the maximum permeability occurs are also comparable with 47 A/m for Metglas and 32 A/m for the ferrite core. For the ferrite core, that exhibits higher hysteresis losses, the asymmetry is more pronounced.

Results of a more illuminating measurement, in which the magnitude of flux swing  $\Delta B$  is maintained constant at 0.1 Tesla by changing the value of the applied field for each bias field, are given in Figure 5 for the Metglas material. Comparison of Figures 2, 3 and 5 shows a dramatic difference in the observed trends. Although the fixed  $\Delta B$  measurements do not represent any real life operating conditions for any material, they provide insight into the loss mechanism. Similar measurements taken on the un-gapped and gapped Mn-Zn ferrite cores are shown in Figure 6. The dc bias dependent losses follow a similar trend for both the un-gapped ferrite and Metglas cores. This result suggests that surface effects and stray field interactions<sup>3</sup> that may be present between the layers of stacked Metglas core are not significantly important parameters. However when the same ferrite core is gapped, a relatively constant loss values at low bias fields followed by an increase at higher dc bias is observed. Introduction of the gap decreases the maximum permeability to 270 and shifts the field where the maximum permeability occurs to 390 A/m. As is clear from Figure 6b that, at this field value, the hysteresis losses begin to increase. Similar fixed  $\Delta B$  measurements on a Sendust core are shown in Figure 7. The measurements only capture the decreasing part of the bias dependent loss curve obtained in Metglas and un-gapped ferrite cores. This is due to the fact that the Sendust core's lower permeability of 120 and higher saturation magnetization prevents the Sendust core from reaching its maximum permeability under the bias conditions employed in this study.

Peculiarities at high external fields have been reported for numerous magnetic systems. In silicon steels, Metglas and Permalloys<sup>4,5</sup>, shape of the hysteresis curve while approaching to saturation differ substantially from the desaturation curve and it is often attributed to asymmetric domain rotation that is caused by different domain structures the material assumes, during forward and backward magnetization. There are studies that report on branching of domains or domain splitting<sup>6</sup> and an increasing number of domain walls at high external fields. Also a decreased reproducibility of domain walls at high external fields is reported by Wadekar and Kramer<sup>7</sup>. Susceptibilities when plotted as  $M$  versus  $1/H$  deviate from linearity at high external fields for crystalline as well as amorphous materials<sup>8,9</sup>.

When a magnetic core is gapped in order to obtain a linear permeability, magnetic flux leakage near the gap introduces orthogonal domains and causes local fluctuations in flux density,  $B$ , both are responsible for increased hysteresis losses<sup>10</sup>. It is possible that the aforementioned peculiarities may arise from creation of similar domain structures at high fields leading to local fluctuations in flux density and increased losses as observed in this study.

Apparently, our current understanding on the physics of domain configuration and energies that drive such behaviors at high fields and possibly correlated higher losses is not well understood. A domain imaging study under applied fields that uses the conditions reported in this study may allow further insight into the micromagnetic mechanisms causing the observed magnetic response under dc bias conditions.

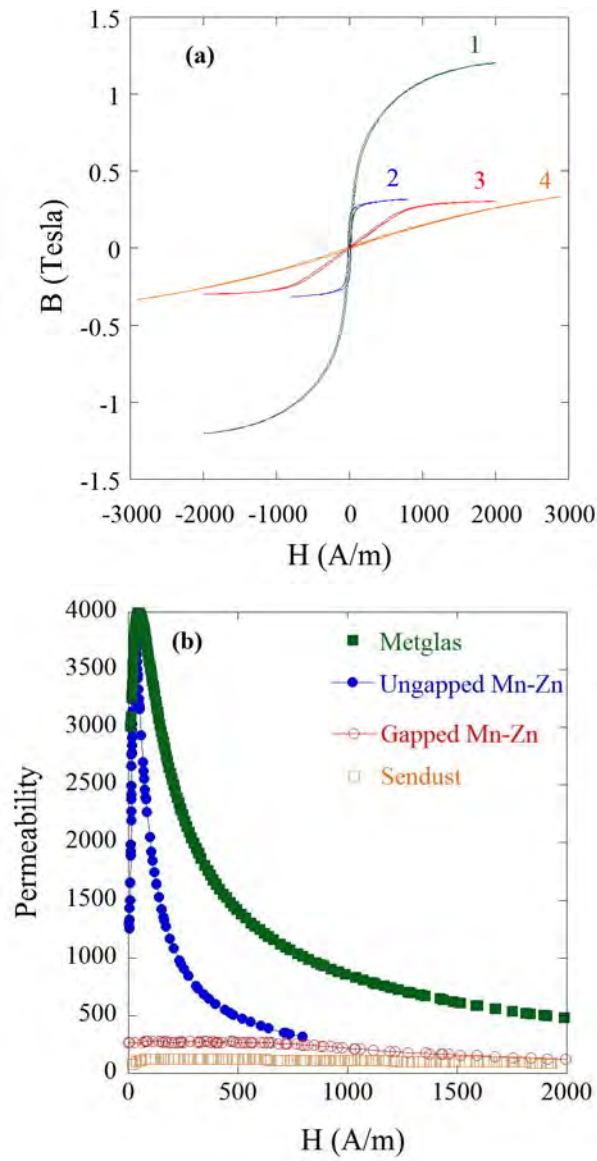
#### IV. CONCLUSIONS

Minor hysteresis loss measurements of three commercially available core materials indicated strong dc bias field dependence. Un-gapped cores, whether crystalline or amorphous exhibited a minima first with increasing bias field, and at higher fields where the magnetization rotation is expected to occur, losses increased. Such observations allow sampling of the magnetic response rooted in different magnetization processes. In particular, the high field rotational magnetization requires further evaluation of the micromagnetic mechanisms causing the microscopic magnetization changes.

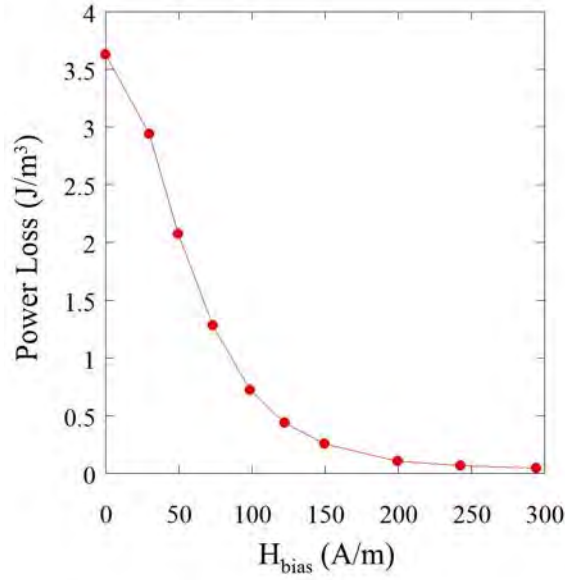
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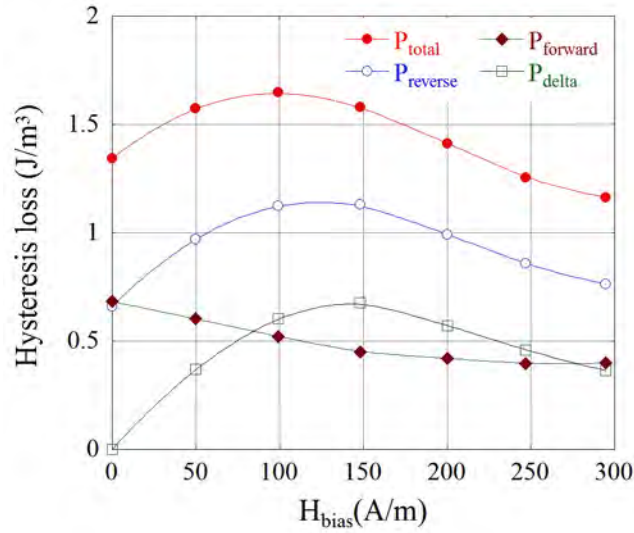
**Figures:**



**Figure 1:** (color online) Whole dc loops (a) and related permeability values (b) of the studied cores. (1-Metglas, 2-Ungapped Mn-Zn ferrite, 3-Gapped Mn-Zn ferrite and 4-Sendust core).

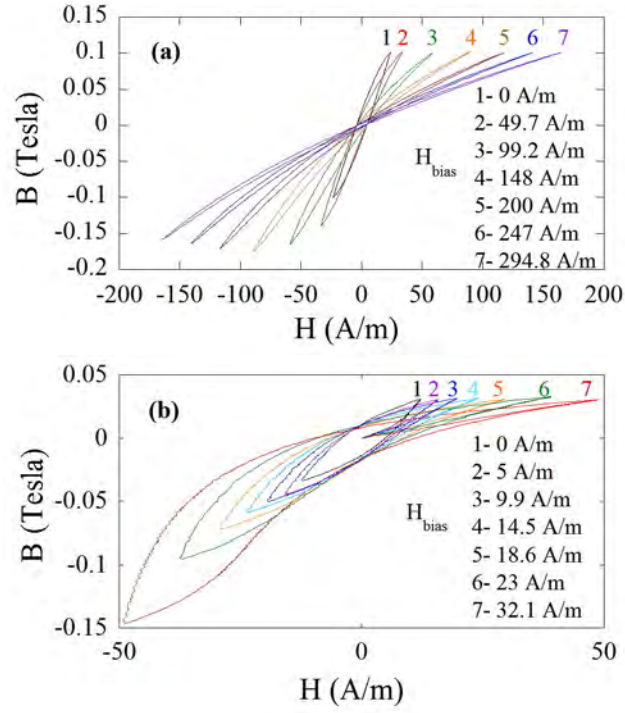


**Figure 2:** (color online) Measured hysteresis losses of a Metglas core as a function of dc bias at a fixed external field of 40 A/m.

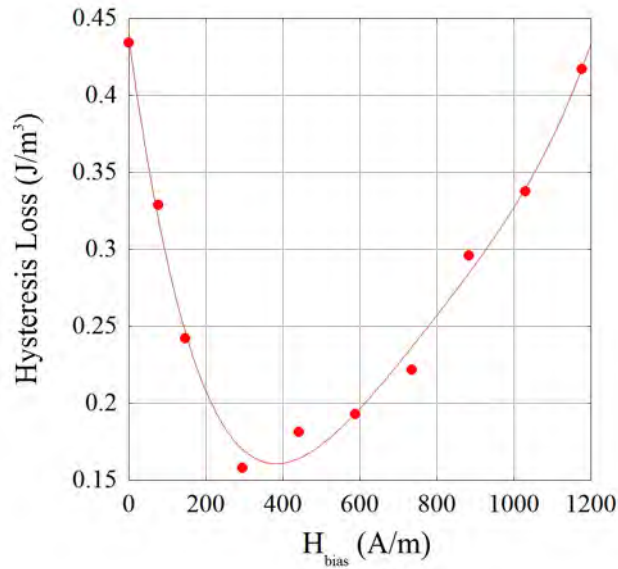


**Figure 3:** (color online) Measured hysteresis losses of a Metglas core as a function of dc bias at a fixed  $B_{\text{max}}$  of 0.1 Tesla. ( $P_{\text{total}}$  is the total loss, and  $P_{\text{delta}}$  is the difference between losses related to forward and reverse magnetization directions).

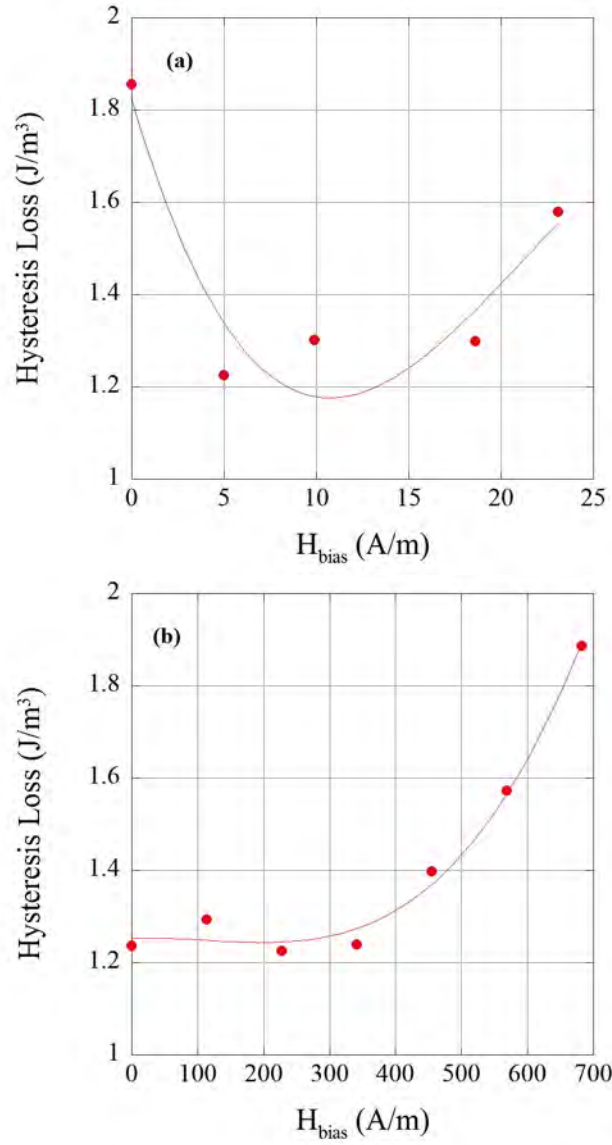




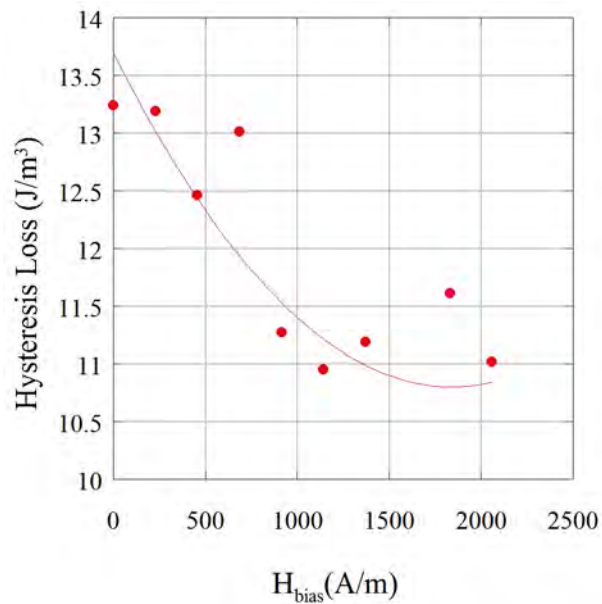
**Figure 4:** (color online) Measured minor hysteresis loops for a Metglas core at  $B_{\max}$  of 0.1T (a) and for the un-gapped Mn-Zn ferrite at a  $B_{\max}$  of 0.03 Tesla (b) for given  $H_{\text{bias}}$  values.



**Figure 5:** (color online) Measured hysteresis losses for the Metglas tape core at a fixed  $\Delta B$  of 0.1 T as a function of bias field.



**Figure 6:** (color online) Bias field dependence of measured hysteresis losses of an un-gapped (a), and gapped (b) Mn-Zn ferrite cores at a fixed  $\Delta B$  of 0.11 T.



**Figure 7:** (color online) Bias field dependence of measured hysteresis losses of a Sendust powder core at a fixed  $\Delta B$  of 0.4 T.